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THE EFFECT OF PRESSURE OF THE CORRODING LIQUID ON THE STRENGTH OF METALS DURING LOW CYCLE FATIGUE TESTING

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Vliyaniye davleniya zhidkoy korrozionnoy sredy na prochnost' metallov pri ispytanii ikh na malotsiklovuyu ustalost'

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THE EFFECT OF PRESSURE OF THE CORRODING LIQUID ON THE STRENGTH OF METALS DURING LOW CYCLE FATIGUE TESTING

[Utkin, V. S., Moroz, L. S., Trudy Severo-Zapodnogo Zaochnogo Politekhnicheskogo Instituta. Prochnost' Materialov (Collection of Works of the North-West Polytechnical Correspondence Institute. Strength of Materials), No. 16, Leningrad, 1971, pages 9-15].

A negative effect of different corroding media, including water, on the strength of materials subjected to variable stresses has been known for some time [1, 2]. /10*

A large number of industrial equipment (pipes, reservoirs, tanks, etc.) are subjected simultaneously to variable stresses and high pressures produced by corroding liquid media. The performance of structural elements under these conditions is lowered, as well as their useful service life.

For example, experimental results of I. V. Kudryavtsev and co-workers [3] showed that the carrying capacity of reservoirs subjected to pulsating pressure of liquids decreases from 110-120 to 50-60 atm., as compared with the static strength.

Similar results were reported in [4] on the effect of pulsating hydrostatic pressure on pipes. In the USA a research has been carried out by marine laboratory on a low cycle fatigue of aluminum and titanium as applicable to marine conditions (different depth) [5].

The effect of the medium pressure was not mentioned in neither of these works. However, the problem remains unclear which of these factors, either the cycling loading, or the pressure of the corroding medium influence the service life of a given equipment. The authors of this article could not find any information on the subject in the literature. Since the effect of high pressures of the corroding media on service life of equipment is of importance, this work was undertaken to study the effect of the water pressure (0-200 atm) on low cycle fatigue of cylindrical specimens (with a circular cut) made of different alloys.

Cylindrical specimens 6 mm in diameter were subjected to pulsating torsion load in liquid media (3% NaCl + H_2O, distilled water) at pressures from 0 to 200 atm. The bottom radius of the circular groove was 0.2 mm,

* numbers in the right-hand margin indicate pagination in the original text

at a depth of 1 mm. Specimens with smooth heads were fixed in a reverser and installed in a thick-walled cylinder with removable bottoms. The cylinder was filled with a water. The compressing pressure of the piston was transformed into a torsion force by use of the reverser. To reduce the resistance of the liquid medium, the latter was supplied to both ends of the cylinder. The pressure was maintained by the MT-2500 unit (pressure measuring instrument). The friction and resistance forces produced by a liquid medium were checked by a multiple loading of the entire test unit, without transfering the load /11 on the reverser and specimens. The pressure was measured by sensors attached to the reverser rods, with outside leads connected to measuring units.

The low cycle loading of 5-6 cycles per minute was produced by a hydraulic test unit equipped with an automatic control. When a specimen was fractured, the base disc of the MT-2500 unit was lifted by 10-15 mm by an excessive pressure and the hydraulic unit was automatically turned off.

Table 1 presents alloys used in these experiments, together with their mechanical properties.

Table 1.

Alloys	Tensile strength, kg/mm^2		Relative contraction, %	
	smooth specimens	grooved specimens	smooth specimens	grooved specimens
15Kh2N3M	115	155	52	14
Titanium alloys based on Ti-6Al	85	120	10	16
L-62	152	52.8	-	31
12N5KhM	152	250	60	14

Figure 1 present experimental results of 15N3Kh2M steel in 3% NaCl + + H_2O in coordinates $\sigma - \log N$ when the pressure was changed from 0 to 200 atm.

Curves in this Figure 1 can be divided into two regions: AB section and the section from the point B to the right. The first section corresponds to high pressures at which the fracture of specimens is accompanied by an extensive plastic deformation which appears as a transverse contraction along the groove. This curve section corresponds to a quasistatic break.

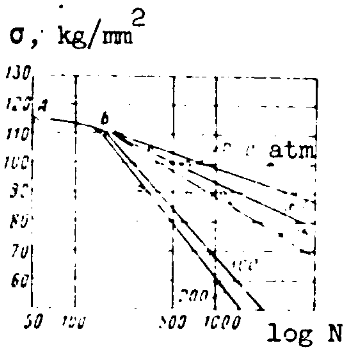

Figure 1

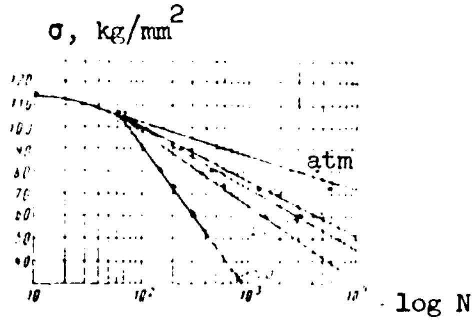

Figure 2

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The second curve section represents the fracture which is accompanied by a considerably lower plastic deformation within the grooved cross section and by appearance and propagation of fatigue cracks. The fracture within the second section is of a typically fatigue nature.

The stress and the number of cycles at the boundary of these curve sections are designated by σ_0 and N_0, respectively. It is evident that when $\sigma_{max} > \sigma_0$, the durability does not depend on an excessive pressure of the liquid medium. This durability decreases noticeably with increasing pressure of the liquid corroding medium when $\sigma_{max} < \sigma_0$. Similar curves for titanium alloy are presented in Figure 2.

Experimental results on static fracture of specimens subjected to different numbers of loading cycles produced by pulsing torsion have shown that a pressure becomes a decisive factor with respect to the life of specimens with the appearance of fatigue cracks. Pressure in this case accelerated the propagation of cracks.

Table 2 presents average propagation rate of fatigue cracks at different pressures of the corroding medium (3% NaCl solution) and identical maximum stress cycles.

Table 2

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Alloy	Pressure, atm.	
	0	100
Steel 3	$3.8 \cdot 10^{-4}$	$5.7 \cdot 10^{-4}$
15Kh2N3M	$1.67 \cdot 10^{-4}$	$4.28 \cdot 10^{-4}$
12N5KhM	$1.0 \cdot 10^{-4}$	$3.8 \cdot 10^{-4}$

Table 3 presents an average number of cycles before fracture of specimens in 3% NaCl solution. Each specimen had a groove 0.1 mm in radius (σ_v^k is the static strength of grooved specimens).

Table 3 /12

Alloy	$\sigma_{max} = 0.58\ \sigma_v^k$		$\sigma_{max} = 0.50\ \sigma_v^k$		$\sigma_{max}\ 0.45\ \sigma_v^k$	
	Pressure, atm.					
	0	100	0	100	0	100
15Kh2N3M	1050	420	2200	610	5000	810
12N5KhM	350	250	620	400	990	600
Ti + 6Al	1500	500	6000	1000	8000	1500

It is evident from Table 3 that a lower σ_{max} decreases the life of specimens due to a medium pressure. This can be attributed to a time factor. The function time of the specimen with a crack and in corrodive medium increases with decreasing σ_{max}. Furthermore, the medium high pressure influences differently various alloys. For example, the durability of specimens made of 15Kh2N3M steel and Ti + 6Al alloy decreases 2.5-3 times and that of 12N5KhM 1.4 times when the pressure increases from 0 to 100 atm at $\sigma_{max} = 0.58\ \sigma_v^k$. At the same time this decrease is 5.1 and 1.65, respectively, for the same metals at $\sigma_{max} = 0.45\ \sigma_v^k$.

Our experiments showed that a different effect produced by high pressures of the liquid medium on alloys depends on an alloy sensitivity to the corroding medium in the absence of the excessive pressure. The pressure in this case accelerates this effect. /13

Increase in the stress concentration accelerates the effect of high pressures of the liquid media. This is attributed to the fact that a lower radius of the groove decreases the critical number of cycles N_0. Table 4 presents values of N_0 for different radii of the groove bottom.

Since an excessive pressure influences the durability of specimens only at the curve section when $N > N_0$ and is ineffective when $N < N_0$, a decrease of N_0 strengthens the activity of the pressure factor.

An exponential dependence between the number of cycles before fracture and maximum stresses for metals tested in 3% NaCl solution at

pressures from 0 to 200 atm. was derived. This dependence is

$$N = N_0 \cdot \exp \frac{\sigma_0 - \sigma_{max}}{k_0 \cdot k_{(p)}} \qquad (1)$$

where k_0 is the coefficient determining the fatigue curve slope to y-axis during testing without an excessive pressure; $k_{(p)}$ is the coefficient which depends only of the medium pressure.

A de: ence of $k_{(p)}$ of the medium pressure can be expressed as

$$k_{(p)} = \exp\ (Ap^B) \qquad (2)$$

where A and B are constant coefficients.

Table 4

Alloy	Groove bottom radius, mm			
	0.1	0.2	1.0	∞
15Kh2N3M	120	150	-	1800
12N5KhM	120	150	-	2500
Steel 3	1040	1200	2000	-

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Table 5 presents values of the $k_{(p)}$ coefficient for specimens having 0.2 mm groove radius. Numerator gives the values of $k_{(p)}$ calculated from formula (2); and the denumerator presents experimental values.

Table 5

Alloy	Pressure, atm						
	0	6	25	50	100	120	200
15Kh2N3M	1	1.495 / 1.540	2.04 / 1.88	-	3.44 / 3.52	-	5.07 / 4.99
12N5KhM	1	1.152 / 1.159	1.350 / 1.390	1.55 /	1.700 / 1.825	1.835 / 1.970	- / 2.120
Ti + 6Al	1	-	1.67 / 1.67	1.77 / 1.76	1.985 / 2.150	-	/ 4.30

The coefficient $k_{(p)}$ can serve as a sensitivity characteristic of metals to high pressure in liquid media.

Let us consider the mechanism of pressures of the liquid media. A low cyclic fatigue of metals in corrodive media, similarly as the usual corrosion fatigue, is due primarily to mechanical and corrosion factors. Therefore, the effect of high pressures of a liquid medium should be always related either to mechanical or corrosion factors, or to both simultaneously. The mechanical factor can be pictured as a splitting effect of liquid molecules in thin cracks. However, experimental data do not verify this explanation. According to these data the greatest effect is produced by the pressure increase of 10-15 atm.; a further increase in pressure does not intensify this effect. The dependence $N = f(p)$ does not mean that the medium pressure is a purely mechanical effect.

Let us consider now the durability of brass (L-62) specimens in 3% NaCl solution and fresh water at atmospheric and high pressures. The average durability results, N, are given in Table 6.

Table 6 /14

Medium	$\sigma = 40$ kg/mm^2		$\sigma = 45$ kg/mm^2		$\sigma = 50$ kg/mm^2	
	Pressure, atm.					
	0	100	0	100	0	100
3% NaCl + H	-	-	1810	950	304	150
H_2O	3435	3335	2065	2465	1507	1448

It follows from this Table that the pressure of 3% NaCl solution decreases the durability of brass while the fresh water does not have this effect.

If we assume that the first medium possesses corrosive as well as mechanical splitting effect (due to pressure), than the second medium differs from the first by the absence of the corrosive effect. But the pressure of the fresh water does not influence the durability of brass and it means that the effect of pressure is not related to a purely mechanical mechanism. A different effect of these two media can be attributed only to their corrosive activity. This was evident from actions of both media on metal without any pressure.

The effect of excessive pressure of liquid media is not related to a purely chemical factor because steels and titanium alloys were not corroded in sea water with increasing pressure [6, 7].

A number of researchers on corrosion fatigue of metals put forward a theory according to which a resistance to the motion of liquids in fatigue cracks decreases and this in turn inhibits the anodic solution of metals at the botton of a newly-formed crack [1, 2].

In this work we verified experimentally this theory. We carried out special experiments with steel 15Kh2N3M at σ_{min} = 0 and 20 kg/mm^2 when the corrodive medium (3% NaCl solution) pressure was 25 atm (Table 7).

Table 7

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σ_{max}, kg/mm^2	σ_{min} = 0 kg/mm^2		σ_{min} = 20 kg/mm^2	
	σ_{av}, kg/mm^2	N	σ_{av}, kg/mm^2	N
100	50	900	60	670
96	48	1200	58	800
90	45	2300	55	1140
85	42.5	3000	52.5	2370
80	40	4100	50	3030

It is known that a metal with identical cyclic load parameters tested in air at σ_{min} = 20 kg/mm^2 increased its durability, as compared with specimens tested at σ_{min} = 0 [8]. This is explained by a decreasing stress amplitude when going from σ_{min} = 0 to σ_{min} = 20 kg/mm^2, despite the fact that σ_{av} increases.

According to Table 7 the picture reverses in a corrodive medium, i.e., the durability decreases at σ_{min}= 20 kg/mm^2, as compared with the durability at σ_{min}= 0. The stress amplitude decreased identically in both cases.

This can be explained by a penetration of liquid medium into a thin crack during constant torsion stresses. This was verified by the following results obtained in this work: (a) a noticeable effect of high pressure of the liquid medium is intensified after fatigue cracks are formed; the pressure facilitates the crack propagation; (b) an increased pressure

accelerates only the effect of corrodive media, without producing any other effects.

The following conclusions can be made on the basis of our results:

1. High pressures of liquid media (3% NaCl solution, H_2O) decrease considerably the durability of metals subjected to pulsating torsion forces (especially of specimens with a circular groove). /15

2. The durability of metals are effected by high pressure of liquid media only when $N > N_0$, i.e., under conditions of a fatigue fracture, and it is ineffective when $N < N_0$, i.e., under conditions of a quasistatic fracture. The effect of pressure is confined primarily to acceleration of the propagation of fatigue cracks.

3. The stress concentration activates the effect of high pressures of liquid media by accelerating the formation of fatigue cracks.

4. Improvement in the contact of the corrodive media with metal cracks is the most probable action of high pressures of the liquid media.

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